SHORT TIME HUMAN TOLERANCE TO SINUSOIDAL VIBRATIONS

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FOREWORD

This report was prepared in support of Project No. 7231, "Acoustic Energy Control," Task No. 71786, "Biological Aspects of Vibratory and Acoustic Energy," administered by the Aero Medical Laboratory, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio

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ABSTRACT

Short time human tolerance criteria for sinusoidal vibration from 1 to 15 cps were determined using 10 healthy male subjects ranging in age from 23 to 34 years. At each frequency, the amplitude was increased at a constant rate from zero to the point where the subject stopped the run because he thought that further increase might cause actual bodily harm. The lower levels of tolerance were found to be between 1 and 2 g at 3 - 4 cps and at 7 - 8 cps. The highest tolerance level of 7 - 8 g was found at 15 cps. Subjective tolerance limits were found to be caused by one or more of seven specific sensations or symptoms. Physiological observations during vibration exposure were also made.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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INTRODUCTION

The effect of mechanical vibrations on man has stimulated much interest for many years. Experimental activity in this field has paralleled the increasing frequency and severity of human exposure to vibrations brought about by motorized transportation and industrial growth. In aviation, the interest concerning the effect of vibrations on pilot, aircrewman and passenger has shifted in recent years from the higher frequency vibrations induced by the motor to low frequency, high amplitude vibrations due to aerodynamic forces. The latter are already a disturbing factor in high speed, low altitude flights (buffeting) and appear to be of vital importance in the launch and re-entry phase of rocket propelled, manned space vehicles.[1] Criteria defining the human limits of comfort, performance and safety in the vibration environments associated with various air- and space-craft missions are needed for the design and operation of these craft.

Previous studies[2,3,4,5,6,7,8,9,10,11] have been designed to determine human response and tolerance to sinusoidal vibrations from 1 to 70 cps. In these studies the subjects were standing, sitting or lying down on the horizontally or vertically vibrating platform. Various subjective responses from the threshold of perception to pain have been defined and used to classify the sensations. Some of the criteria were: just perceptible, definitely perceptible, noticeable, unpleasant, annoying, objectionable, exceedingly annoying, painful and unbearable. It is obvious that these terms are wide open to subjective interpretations and are only to provide a general classification of the perceived sensations. In analyzing the results of several investigators in terms of willingness of a subject to tolerate various levels of vertical vibrations, Goldman[6] shows that the variability among different studies is very great.

Assuming that environmental conditions were kept constant the most important factors effecting variations in the response to vibrations are: experimental procedure, exposure time, body posture and arm positioning, type of seat, seat belt and harness, and clothing. The studies summarized by Goldman probably had exposure time and experimental procedure as main variables, and no special effort had been made in these studies to increase tolerance by proper seating and protection, two areas still open for study. It is conceivable that vibration levels, which might be judged annoying, when exposed to them for a few minutes, become painful and intolerable after half an hour or hours. The absolute highest tolerance levels are to be expected for extremely short exposure time. The purpose of this study was to find this short-time limit of subjective, voluntary tolerance for vertical vibrations and to define this tolerance. The frequency range from 1 to 15 cps was selected because buffeting and impact loads make short-time exposure for seconds or fractions of a second in this range especially important. Tolerance is therefore defined as the degree of stress human subjects are willing to undergo without noticeable injury. Since maximum tolerance limits for military applications were desired, standard seat and harness were selected accordingly, but in no way constitute optimum designs to increase vibration tolerance.

The tolerance levels obtained are considerably higher than previous results under different conditions, especially longer exposure times. This study can only be considered the beginning of a series of time-tolerance studies, which, for practical applications, will have to be extended to the field of random, wide band vibrations as well. These studies are supplemented by animal experiments[11,12] using vibrations above the tolerance level established here, so that severe physiological and pathological effects can be studied and correlated with the first danger symptoms observed in approaching the tolerance limit. The few known cases in the literature where humans have been exposed to levels clearly above the tolerance limit[13], as defined here, also help to verify this limit.

Subjects

A panel of 10 members was assembled. The subjects were not asked to join the panel; they independently volunteered to participate in the experiment. Their ages ranged from 23 to 34 years, their weights from 143 to 210 pounds and their heights from 5 ft. 7 in. to 6 ft. 3 in. (table I).

TABLE I

VITAL MEASUREMENTS OF TEST SUBJECTS

SUBJECT	AGE	WEIGHT lb	HEIGHT ft.	HEIGHT in.
BW	32	195	6	0
CR	24	136	5	11
DF	23	200	6	1
EW	29	150	5	9
HR	34	200	5	10
LJ	25	143	5	7
ME	28	210	6	0
RE	28	145	5	7
RM	24	168	6	0
SR	27	197	6	3

Experimental Equipment

All vibrations used in this experiment were sinusoidal in nature. A Western Gear mechanical shake table (fig. 1) was utilized to attain frequencies ranging from 3 to 15 cps. With this machine, it was possible to attain an excursion in the vertical plane anywhere from 0 to 22 cm. The amplitude may only be increased from zero to any point up to 22 cm D.A.* at a constant rate of 0.75 mm D.A./sec characteristic of the machine; conversely, the amplitude may be decreased anywhere from 22 cm D.A. to 0 at the same constant rate. The shake table may also be run at constant frequency and amplitude within the above described range. The frequency and amplitude are directly read from the shake table instrumentation. Additional instrumentation for the device consisted of an accelerometer mounted on the vibrating platform where the subject was seated. The accelerometer was connected to an oscilloscope so that acceleration could be observed for monitoring purposes.

At 1 and 2 cps the amplitude necessary to reach tolerance could not be obtained on the shake table, therefore, the "Vertical Accelerator" (fig. 2) was used for this part of the experiment. This device can produce vertical sinusoidal motions with an amplitude of ± 10 feet D.A. with an acceleration limitation of ± 3.5 g up to 7 cps; random noise patterns can also be reproduced. The seating arrangement is identical to the shake table. The only difference is that the subject wears a standard Air Force crash helmet with an intercommunication system so that he may converse with the operator and medical observer.

The subjects were seated to simulate the position of a passenger in normal flight, although during space flight the passenger will probably assume a semi-recumbent position. A modified T-33 jet aircraft seat was mounted to the vibrating platform; the seat is made of reinforced flat plywood board and no cushions were used. With this the true motion of the vibrating platform was transferred to the subject with a minimum of change. The subject sat with his coccyx pressed firmly against the back of the seat so that a nearly vertical position was maintained during the run. He was strapped into the chair with a standard Air Force lap belt and shoulder harness which were tightened so that the subject could not move in either the vertical or horizontal directions. Care was taken to avoid impairing respiratory movements, and the vibratory characteristics of the abdomen and its contents were changed as little as possible. The subject's feet were strapped down snugly to the vibrating platform. The thighs were not supported from the buttocks down (fig. 2). The head was not supported although a head rest was attached to the seat to safeguard against severe vacillations.

The subject was able to grip the extended arm rests where a signal button was conveniently located. When the button was pushed, a buzzer signaled the operator to stop the run immediately.

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*Double Amplitude

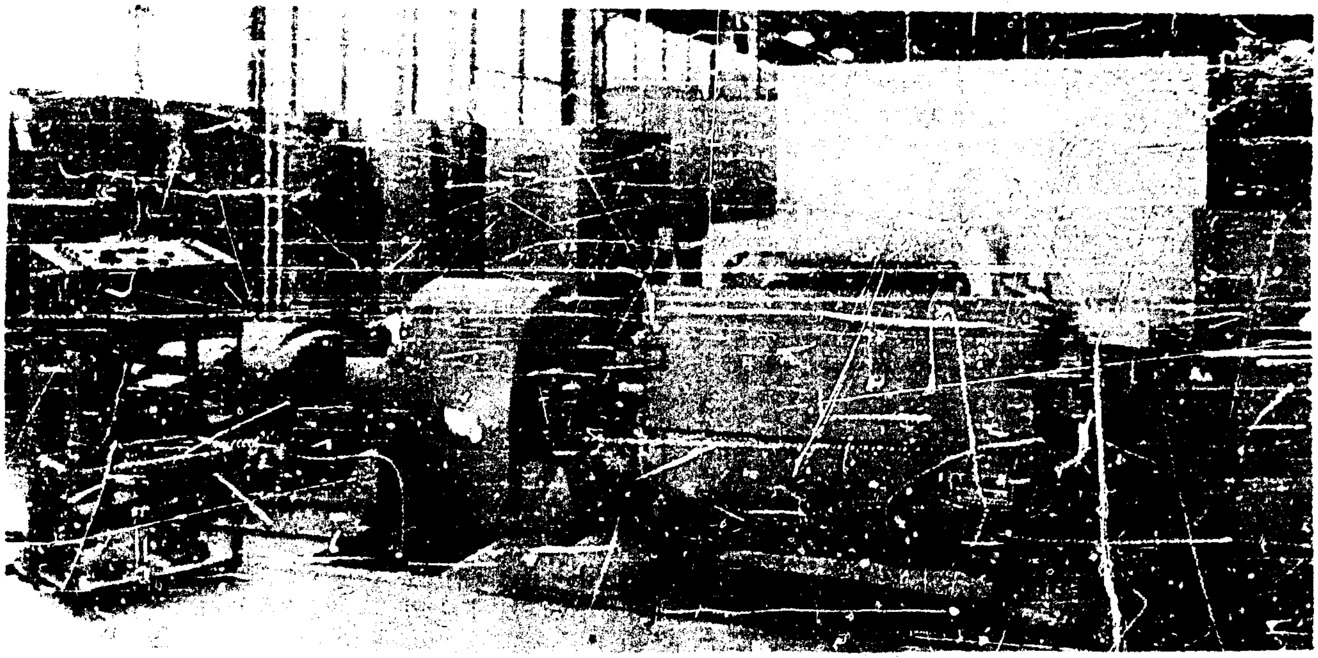

Figure 1. Western Gear Mechanical Shake Table on which a T-33 Jet Aircraft Seat was Mounted.

Figure 2. (left)

Vertical Accelerator.

Subject is shown in the position assumed for all runs in a T-33 modified jet aircraft seat attached to vibrating platform. Subject has constant communication with the medical observer and operator. Emergency buttons are located bilaterally at end of arm rest.

Experimental Procedure

The frequencies were preset and remained constant throughout the run. The run began by increasing the amplitude from zero; due to the large displacements used at 1 and 2 cps, the amplitude was increased at a constant rate of 10 mm/sec D.A. When tolerance was reached the subject pressed the buzzer button which signaled the operator to stop the run immediately. At this point, the amplitude was read.

The panel members were introduced to the problems of flight under the influence of low-frequency vibrations. They were familiarized with the Vertical Accelerator and the shake table by having preliminary rides at various frequencies considerably below tolerance levels.

The subjects were then briefed on the experimental procedure. It was made especially clear that this study was attempting to define the limit of sinusoidal acceleration at various frequencies a rider would be willing to undergo before it was thought that actual body harm would occur. It was further emphasized that the limit of sinusoidal acceleration was not discomfort. The subjects were not given information as to what sensations they could experience. The panel members, with the exception of the one medical officer, had no insight into symptomology. Immediately after each run the subjects were asked to give their reason and describe in detail the sensations which were the primary cause for stopping the run; care was taken to keep prompting at a minimum. The criteria of tolerance for this experiment, therefore, were completely subjective, i.e., completely dependent upon any sensations the subject might encounter. When it could not be decided which sensations were more pronounced, more than one reason was given for discontinuing the run. Since the maximum obtainable acceleration on the Vertical Accelerator, at the time of this study, was slightly under tolerance limit at 1 and 2 cps, the subjects were asked how close they were to their tolerance limit. Each rider estimated that his tolerance was very near to being reached. Accordingly, the tolerance limits at these two frequencies have been empirically determined.

A medical officer was stationed next to the shake table so that direct communication was easily maintained; or on a platform opposite the center line of the Vertical Accelerator near the path of its carriage. Here the observer had constant phone communication with the rider and operator. His duty was to stop the run if the subject elicited signs of bodily harm. Blood pressure, pulse rate, respiration and ECG were observed before and after the run to take heed of any abnormalities that might arise and to observe lasting physiological phenomena. Blood pressure was taken by the auscultatory method. An attempt was made to obtain pulse rate and ECG tracings during the run. These tracings met with little success because of extreme muscular activity encountered during the run.

Each subject was exposed to 11 rides, which consisted of two frequencies per day. The range from 1 to 10 cps was covered in 1-cycle steps; the 11th frequency was 15 cps. The sequence of exposure to these frequencies was randomly chosen. The subjects were asked to report any lasting symptoms or observations on the days following the runs. But no such reports were received.

The results are presented in figure 3. They consist of the arithmetic mean, the standard deviation of the mean and the extreme g values found for each frequency.

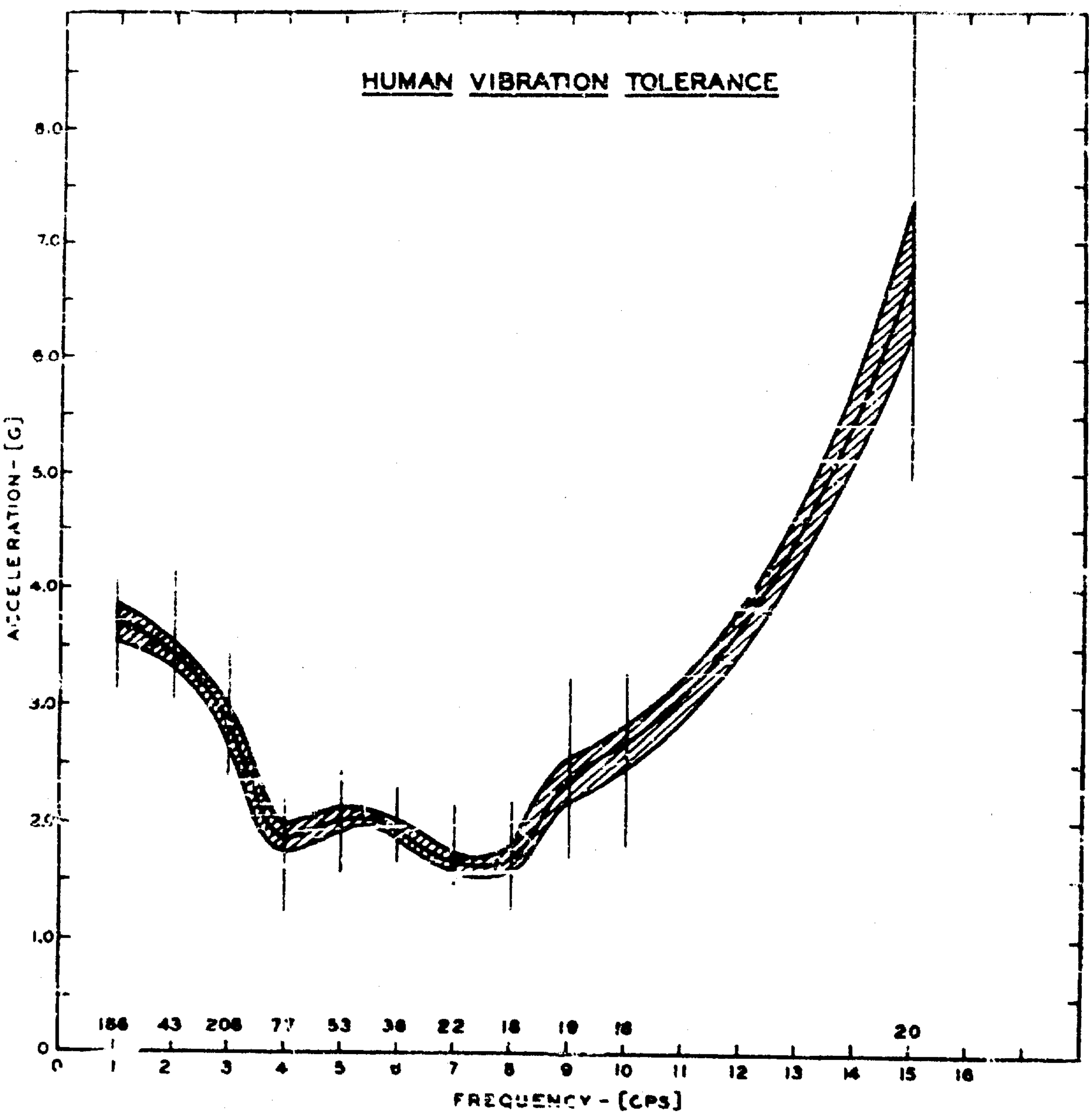

Figure 3. Arithmetic Mean, Standard Deviation, Maximum Deviation of Tolerance Values. Arithmetic mean of exposure time in seconds is indicated above the frequency scale for each test frequency.

Table II lists the reasons given by the subjects for stopping the run. There are seven sensations or symptoms, four of which are pain referable to a specific region, i.e., head, chest, abdomen and testicles. The remaining three sensations are void of pain, i.e., dyspnea, referable to the respiratory system, discomfort referable to a generalized condition, and anxiety, suggesting a generalized psychological response. Reviewing the symptoms of the subjects aids in elucidating the physiological mechanisms.

TABLE II

CRITERIA OF TOLERANCE

CYCLES PER SECOND	SYMPTOMS						
	Abdominal Pain	Chest Pain	Testicular Pain	Head Symptoms	Dyspnea	Anxiety	General Discomfort
1					X X X X X X X X		X X X
2					X X X X X X X X		X X X X
3	X X	X X			X X X X X	X	X X X X X
4	X X	X X		X X	X X X	X X	X X X X X
5		X X X X				X	X X X X X X
6	X X X	X X X X		X			X X X X
7	X X	X X X X X	X	X			X
8	X	X X X X		X		X X	X X X
9	X X	X X X X			X		X X X X X
10	X	X	X X X	X X		X	
15							X X X X X X X X

All subjects experienced the sensation of displacement of the body and its parts during the run. This sensation was mentioned as the limiting factor, alone or in combination with other symptoms, only when the intensity of the displacements became so severe that it was thought bodily damage might occur. The abdominal pain had a slow onset, was dull and aching in nature, and gradually increased in intensity as the run continued. The pain distribution was about or below the umbilicus and often described as "gas pains." The chest pain had a distribution suggestive of the pain experienced in coronary heart disease, i.e., dull, aching pain which increased in intensity as the ride continued. The pain occurred at the substernal or precordial areas and frequently extended across the entire chest. However, in some cases this pain was intensified by respiratory movements, although not to the extent of interfering with respiration. Testicular pain was described as pain of the groin, being collicy in nature. The head sensation was described as a dull, aching pain of low intensity or a full congested feeling, as if the head were expanding somewhat.

To summarize, all of the above pain sensations were described as having a subtle onset, being dull in nature, of low intensity and increasing with crescendo-like characteristic. With the preceding description it is observed that the end point or tolerance level was attained well after the above symptoms commenced, therefore the pain had attained qualities of such proportions that the subject thought by continuing the run any further, bodily harm would result. The pain sensations ceased after the run except for head pains which lasted several minutes.

Dyspnea and general discomfort had an onset similar to the painful sensations, a slow insidious onset building up to an unbearable intensity. The respiratory movements were described as being impaired to such an extent that all of the subject's attention was focused on overcoming the rapid displacements of the thorax and abdomen which inhibited gaseous exchange.

General discomfort was described as the sensation of various body parts -- muscles, joints, thorax and abdomen -- being torn or falling apart.

After experiencing the first rides the subjects developed and maintained a state of mild anxiety toward the runs throughout the rest of the experiment. There were seven episodes where the subjects felt that tolerance was based on extreme anxiety.

By comparing the values before and after each run, pulse rate was observed to increase as much as 15 beats per minute and blood pressure showed an increase as much as 10 mm of Hg. which quickly returned to normal. The ECG showed a compensatory bradycardia following the increased heart rate soon after each run. No abnormal ECG pattern was observed throughout the experiment. Vertigo and "seasickness" were not experienced during this study.

DISCUSSION

Inasmuch as tolerance is defined by the degree of stress human subjects are willing to undergo (rather than by measurable changes of physiological functions which actually would indicate that the limit of tolerance had been exceeded), the subjective response of the test subjects was chosen as the criterion of tolerance. Despite the fact that the results of this study were widely dependent upon the individual's psyche and the subjective conditions prevailing at the times of the experiment, the spread of the curve is surprisingly small (fig. 3, p. 8). It suggests that different individuals are somehow similarly affected by the same type of vibratory stimulation. Two factors, discussed below, may be responsible for this similarity of responses.

First, the human body as a mechanical system represents a complex spring-mass system. The body types of the subjects with respect to their mechanical properties were fairly consistent and characteristics of this spring-mass system may be assumed in the same order of magnitude as shown by impedance measurements.[10,15] The variations of the mechanical characteristics of different test subjects in the same position are indeed small. Hence, it may be expected that the mechanical response of the body of all subjects to an identical mechanical stimulus and the resulting energy transmission is fairly consistent, too.

Second, the thresholds for proprioception and for perception of pain are characteristic of the species and deviations would be expected to be small.

The adequate stimulus for both proprioception and pain perception on which, generally, the criteria of tolerance in this study are based, is the effect of displacement on the body, i.e., relative displacement of different tissue complexes with respect to each other. Both proprioception and pain are quantitative sensations depending upon the degree of displacement and/or the number of receptors affected. They represent a continuum of sensations with overlapping which acts as an excellent informative and protective mechanism. By applying these facts to the problems of vibration it becomes apparent that the subjective tolerances found at various frequencies are determined by the degree of displacement occurring at specific body regions. On this basis an explanation of the symptoms the test subjects experienced at tolerance levels may be attempted.

1. Abdominal pain is believed to be caused by stretching of the terminal ileum, cecum and hepatic flexure of the large intestines and its supporting mesentery.

2. Chest pain which most commonly occurred between 5 and 9 cps could easily have its origin from mechanical stimulation of the vibrating heart on the diaphragmatic pericardium and on the parietal pericardium about the base of the heart, and/or from stretching of the major vessels and their supporting structures due to displacement. Displacement of the diaphragm at its anterior attachments is also believed to be a source of pain.

3. Testical pain is evoked by stretching the spermatic cord resulting from the cyclic excursion of the testicles and its surrounding tissues. The displacement necessary to elicit unbearable pain is very small because of its pain fiber characteristics and distribution.

4. Head symptoms are more difficult to evaluate. Part of the sensation is probably due to the displacement of the facial skin and the subcutaneous fat layers about the underlying bony structures. What part the brain, the spinal cord and especially spinal fluid play in the origin of head symptoms is yet to be determined.

5. Dyspnea which occurred exclusively in the low frequency range, i.e., between 1 and 4 cps, is undoubtedly a result of the cyclic motions of the thoraco-abdominal system.[14] Active respiration was made very difficult by the vibratory force acting on the abdominal mass thereby decreasing diaphragmatic movement and on the thoracic cage decreasing thoracic volume. The amplitude of this passive respiration was such that the air column oscillated proportionately more within the trachea and bronchial tree, thereby decreasing gaseous exchange.

6. Anxiety was probably caused by a multiplicity of reasons among which severe stimulation of the proprioceptive system and respiratory impairment play important roles.

7. General discomfort, under which various sensations of a more diffuse character were listed, occurred over the entire frequency range. Most commonly it was described as a feeling of "falling apart" of muscles and joints. These are sensations referable to the system of proprioception.

For all runs (regardless of the type of symptom which finally determined the limit of tolerance) at higher acceleration levels the subjects were unable to perform activities other than exerting extreme effort in flexing their skeletal and abdominal musculature to "control" themselves. Near the end of most runs it was noticed that the Valsalva maneuver was performed. This apparent basic reflex of muscle flexing under the influence of severe vibration stiffens the body in order to more effectively resist the stimulus which becomes increasingly intolerable. The degree of exercise over a short period of time explains the changes in blood pressure, heart rate and breathing following each run.

Comparing the tolerance curve (fig. 3) derived from this study with the results of impedance measurements[10,15] a similarity in general characteristics can be observed. Both ends of the tolerance curve exhibit steep increases in the same frequency range where the body impedance decreases. The minimum tolerance found at 4 cps is in agreement with a maximum of impedance at the same frequency. The second minimum of tolerance found at 7-8 cps, which might be referable to a natural frequency of the heart, does not agree with an increase of impedance.

The tolerance curve derived from this study is compared in figure 4 with tolerance curves previously reported.[2,3,5,9,10] Little similarity can be found in either the general characteristics of the curves or in the order of magnitude. The reason for the disagreement is based upon the difference in experimental procedure applied in this study:

1) Short exposure time

2) Sitting arrangement

3) Use of a lap belt and shoulder harness

It is hoped that additional studies of tolerance levels for increasingly longer exposure times and with various seat and harness arrangements will answer the questions raised by these results.

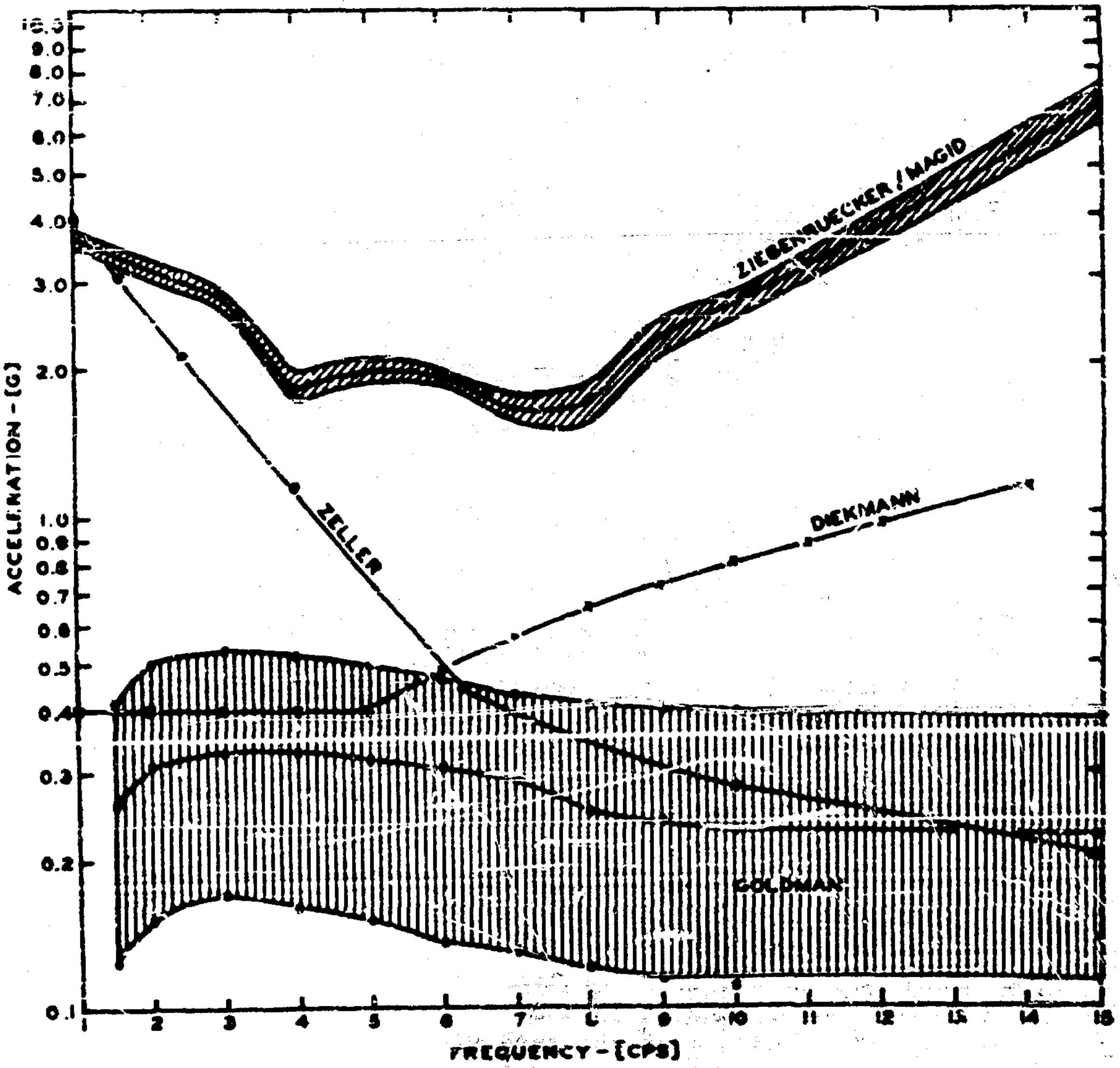

Figure 4. Tolerance Curves

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